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Improved Structural Design Using Evolutionary Finite Element Modeling

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Abstract

A wing structural layout design experiment conducted with a commercial aircraft manufacturer indicates that a systematic, evolutionary structural design process helps to focus integrated discussion, analysis, and decision-making efforts. The process systematically incorporates optimized structural information into the design process. The technical complexity of aircraft design requires technically skilled individuals to communicate disciplinary needs to people outside of their own disciplines. Tools and methods that help interdisciplinary information transfer and can evolve with the fidelity required by the design process will improve a design organization's capability to produce an integrated aircraft that meets all of design requirements. This paper shows that advanced structural design tools, used in a multidisciplinary team setting, will improve structural information generation and communication. This will enable a design team to better identify and meet structural design requirements. A realistic example demonstrates how high fidelity computational structural tools can generate and communicate structural information appropriate to the process needs. This means that the information is actually used to make decisions.

Introduction

Improving the aircraft development process will produce higher quality, innovative designs faster and at lower cost.

In this paper we examine structural design process needs and tool requirements and then explore a wing structural design problem. For design we define a systematic process for evolving structural detail that integrates physics-based structural analysis and optimization with experience to support higher-quality fact-based design decisions. Finally, we present the results of this approach applied to the design of a wing structural layout for a business jet. This work augments earlier work by Taylor and Weisshaar[1].

Aircraft Structural Design Process

As an aircraft structural design evolves, the need for structural definition and loads definition increases. As a result, design freedom is reduced as it is traded for design fidelity. In early design phases, designers can make decisions and changes relatively easily, but the design lacks fidelity so the team cannot

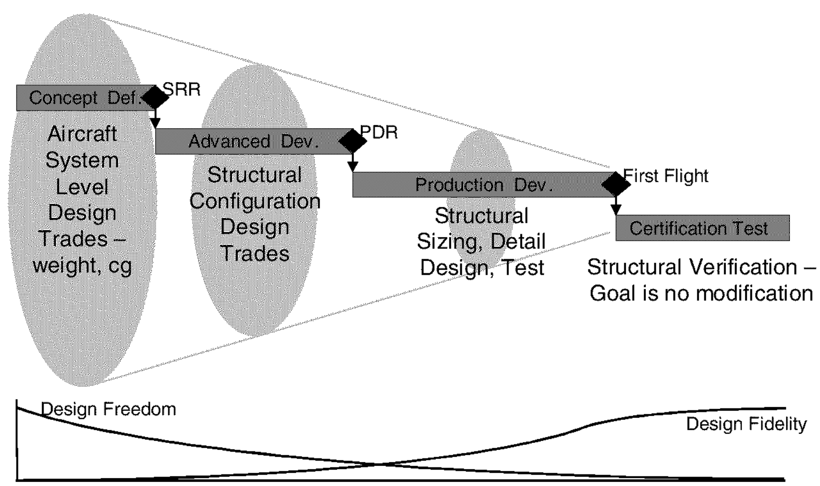

Figure 1—Design process structural needs

Paper presented at the RTO AVT Symposium on "Reduction of Military Vehicle Acquisition Time and Cost through Advanced Modelling and Virtual Simulation", held in Paris, France, 22-25 April 2002, and published in RTO-MP-089.

fully evaluate the impact of these decisions on product cost, manufacturing details and quality. When design fidelity finally appears later it may conflict with earlier assumptions; the cost of design changes to bring these objectives back into alignment is large.

Whitney[2] observes that design is both an organizational and a technical activity; successful design processes must integrate tools and information from both aspects of design. Process definition provides the foundation for successful integration and application of technical and organizational tools and methods. In a well-designed process, core knowledge - in the form of people and tools - exists at the appropriate places to meet process information needs and dependencies. The customer ultimately defines product quality. The design process, through customer-oriented requirements and design traceability, must reflect this definition.

As shown in Figure 1, system design evolution places requirements on the structural design process, from early design trades to detail design and verification later in the process.

These process needs place requirements on structural tools and models. As shown in Figure 2, structural models reflect systems engineering process needs by evolving from broad conceptualizations that enable exploration of the design space. The systems engineering process[3] establishes a formal evolution of detail and flow of information, promoting design activities that provide the level of detail and fidelity specified by requirements. Information quantity and quality will increase and evolve as the design moves through the funnel.

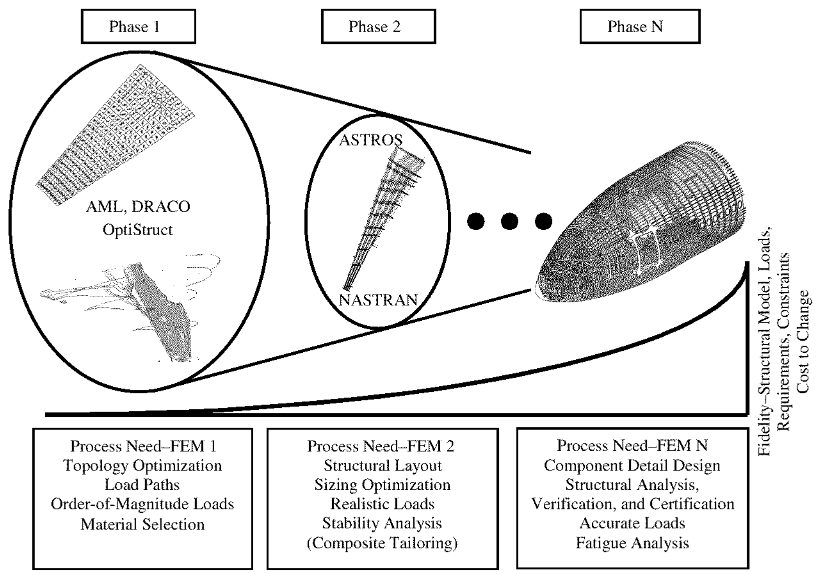

Figure 2—Structural design funnel

At the beginning of the structural design process (Phase 1) structural designers need information, either from tools or experience, to guide configuration and topology decisions to determine the number of ribs and spars and their locations and orientations. This phase is marked by conceptualization and creativity. The latter part of the process (Phases 2 through N) involves structural member sizing, optimization and analysis. Information for later activities requires increasingly greater model fidelity and detail

Effective, appropriate tools to meet the specific needs of each phase will improve the structural design process. Identification of what questions structural design tools answer, what level of structural detail must be input, and what level of structural fidelity results leads to an understanding of the specific value added by each tool set and areas for improvement.

Tools and models that generate and communicate physics-based structural information early in the process elevate the level of the structural design task so that structural issues, and therefore manufacturing and cost issues, can impact top-level aircraft configuration and design. Phase 1 tools must provide quick, communicable, modifiable, and deployable structural information given low-fidelity geometric and loading input. To lay out structural members effectively, structural designers need load path information. Moreover, to interact with non-structural design team members and requirements, structural designers need to be able to present this load path information in a clear, graphical form. Furthermore, to be useful in the early conceptual phase, structural models must become the equivalent of the “back of the envelope” calculation, providing results to evaluate feasibility in real time. Finally, when the time for conceptualization is over, the models must be seamlessly deployable, evolving directly into the models necessary for the remainder of the structural development process.

Background

Multidisciplinary teams drive projects through aircraft development because of the complexity of product and process and the need for technical specialization. However, such teams face tremendous challenges that accentuate the need to integrate organizational and technical activities

Waszak, *et al.*[4] use a systems thinking approach[5] to model multidisciplinary team dynamics and then identify six key determinants of team effectiveness. The present paper addresses methods for improving two of these determinants: effectiveness of team processes; and, balanced levels of technology.

A systematic design process using *structured* design methods (as opposed to *structural* design methods) improves the 'effectiveness of team processes' determinant by formalizing and managing information flow throughout the team, providing insight into design problem structure and a baseline for understanding and improving the design process. Systematic approaches formalize information flow, promoting communication so team members share mental models and learning. In addition, systematic approaches are self-documenting, preserving learning at each stage of design progression.

Systematic approaches clarify the customer's "voice" to team members so they can identify how their function traces back to and adds value to the customer. This clarification pushes the issue of quality upstream into the design process itself, which is much more effective than fixing the design product after the fact[6].

Research in structured design methods is very active; the design and engineering management literature contains many references which provide a scientific foundation to design, for example: Ulrich and Eppinger[7], Eppinger[8], Pugh[9], Dym[10], Cross[11], and many others. Alexander[12] and Simon[13] discuss the nature of design problems.

A Structural Design Process Model

Traditionally, the aircraft preliminary design phase lays out structural configurations based on the insight of experienced designers. Analytical structural design tools enter the process only when system-level design is concluded or near conclusion, so their impact on the aircraft outer mold-line configuration is minimal.

Conventional use of finite element methods depends on detailed models that require large time investments and depend on detailed geometric models. By the time finite element results are available the design team has already committed to a structural configuration. Engineers can use these results to perform sizing optimization, subsystem-level design, and analysis, but the opportunity for configuration design trade studies based on theory has passed.

Weisshaar and Komarov[14] advocate modification of the traditional aircraft design process to include structural theory early by generating load path information in a preliminary finite element optimization model (FEM I). Structural designers then use this load path information as the basis for structural configuration and a more detailed, traditional finite element model (FEM II) of the load carrying structure for shape and sizing optimization.

Structural detail evolves through a series of finite element analysis and optimization activities (FEM 1-FEM N) alternating with team-based design activities (Design 1-Design N). This is opposed to the traditional method of specifying full detail and constraints in the first structural model, locking in details before design trades can be made and neglecting nonstructural requirements in the analysis. At the end of the process, the documented evolution of concepts and evaluation enables traceability of design decisions.

Wing Structural Layout Design Process Experiment

A design experiment was performed at Raytheon Aircraft in Wichita, Kansas to test the validity of a new structural design process that incorporates early-on use of finite element models. Technical team supporting this process included personnel from loads, structural integrity, producibility engineering, and geometric configuration. Our process is described in the ensuing sections.

Wing Structural Design—Problem Definition

The wing structure has weight and cost objectives but must meet requirements and constraints consistent with the aircraft mission and FAA certification. To begin our process, a document was drafted to communicate wing structural requirements to project participants. This document provides the foundation for design and analysis activities, establishing metrics, target values, and scope of the project. The requirements established by this document also flow to lower-level design activities as part of the systems engineering process.

This project focused on primary wing structure and considered additional structure only as it influenced wing structure through interfaces or constraints. For example, flap and aileron structure was not considered. Loads from flap and aileron attachments, however, were applied through flap tracks, hinges, and actuators as appropriate.

Requirements for the wing structural design include the 7 categories shown in the panel below:

Requirements list

1. Structural Performance
   1.1. Stiffness
   1.2. Deflection
   1.3. Strength
   1.4. Durability
   1.5. Structural Stability
   1.6. Geometric Interface
2. Environmental
   2.1. Loads
   2.2. Ground Wind Gust Durability and Protection
   2.3. Lightning Strike Protection
   2.4. Ice Protection
   2.5. Fuel Slosh and Vibration
3. Size
   3.1. Dimensions
   3.2. Weight
   3.3. Fuel Volume
4. Costs
   4.1. Recurring Costs
   4.2. Direct Operating Costs
   4.3. Producibility and Process Characteristics
5. Support
   5.1. Service Life
   5.2. Structural Inspection
   5.3. Towing, Jacking, and Hoisting
   5.4. Reliability
   5.5. Maintainability
6. Safety
   6.1. System Safety
   6.2. Fire Safety
   6.3. Crash Safety
   6.4. Bird Strike
   6.5. Emergency Egress
7. Certification

Because loads and constraints drive the structural configuration design, choosing the correct, representative set of load cases is critical to designing structure that can evolve into an optimal system whose form fits its function. Too many loads with too much fidelity restrict the design freedom needed to satisfactorily explore the design space during conceptual design. Conversely, insufficient fidelity in load number or distribution leads to missed or misplaced structural connections. Load fidelity must match requirement and design levels of detail within the systems engineering process.

The 5 load cases applied in our experiment were:

1. *Static landing with flaps, maximum positive torque and shear*
2. *Head on gust, landing with flaps, maximum negative torque*
3. *Dynamic gust at cruise, maximum negative bending moment*
4. *Dynamic gust at cruise, maximum positive bending moment*
5. *Static Maneuver, maximum positive torque and shear*

Concept selection without structural analysis

Our design team came from two different experience areas. Part of the team came from a culture that favored multi-spar design, preferring a many spar concept, while others came from a different culture that favored two-spar wings. In the beginning, a design decision based solely on experiential input would have been contentious.

The Weighted Objectives Method is a useful structured design technique. The table in Figure 3 shows a hypothetical weighted objectives scoring matrix that might have resulted if the inputs to this method were based solely on experience. Inputs into this matrix based solely on previous experience lead to little differentiation among the concepts and consequently no basis for a design decision. Inserting finite element "physics-based" information will change this, as we shall see.

Wing Structural Design—Solution Synthesis

Figure 4 depicts the cycle of design and analysis activities used by our process. This section will describe each phase of the process and present results from each phase.

Structural finite element analysis and optimization models address configuration layout with stress constraints. Presentation of these results to project participants generates knowledge feedback to modify the models, generate new practical structural concepts, and evaluate these concepts for manufacturing. This iteration between analysis and design activities is repeated through a series of models and evolves into models with greater configuration detail and additional analytical constraints. The first level of detail develops structural members driven by stress, such as spar webs and skin thicknesses. The next level of detail adds buckling and deflection constraints, defining ribs and stiffener design.

	weight factor	2 Spar raw	2 Spar wtd	3 Spar raw	3 Spar wtd	4 Spar raw	4 Spar wtd	7 Spar raw	7 Spar wtd
Weight	0.30	0	-	0	-	0	-	0	-
Stiffness		0	-	0	-	0	-	0	-
Fuel Volume		4	-	3	-	2	-	1	-
Cost	0.30	3	0.90	2	0.60	2	0.60	3	0.90
Fabrication		4	-	3	-	2	-	1	-
Assembly		1	-	2	-	3	-	4	-
Accessibility	0.05	4	0.20	3	0.15	2.5	0.13	1	0.05
Inspection		4	-	4	-	2	-	1	-
Maintenance		4	-	2	-	3	-	1	-
Fuel Considerations	0.05	2	0.10	4	0.20	3	0.15	1	0.05
Certification Issues			-		-		-		-
fail safe	0.25	1	0.25	4	1.00	4	1.00	4	1.00
verification	0.05	4	0.20	3	0.15	2	0.10	1	0.05
Weighted Sum	1.00		1.65		2.10		1.98		2.05

Figure 3—Scoring matrix with low quality information input

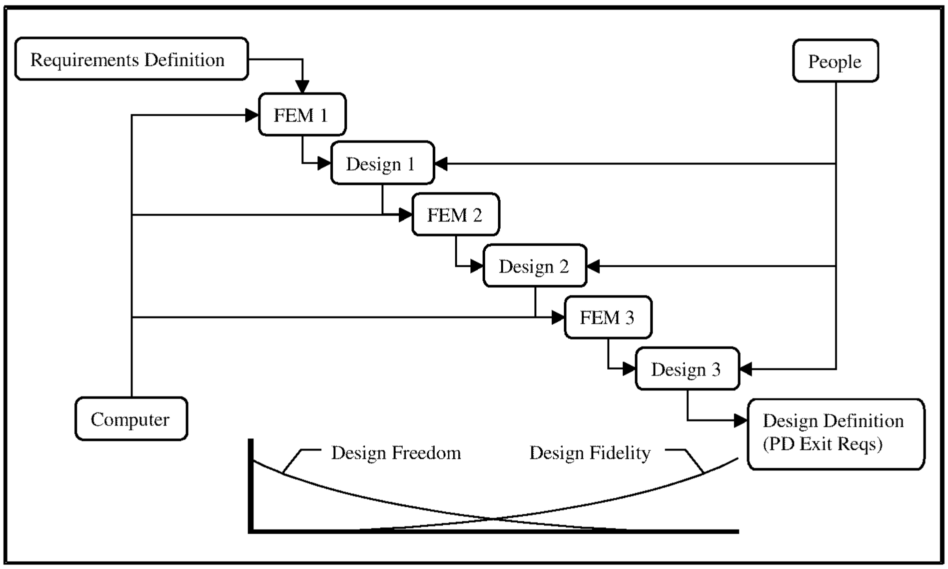

Figure 4—Alternating evolutionary finite element models and design activities for design process experiment

Phase 1

The goal of Phase 1 activities is to provide high quality structural feedback during aircraft system-level design activities; traditionally this phase has only historical weight and center-of-gravity structural input. Phase 1 models provide meaningful structural feedback as early as possible with as little internal geometric definition as possible.

The purpose of the first finite element model, FEM 1, is to generate information about load paths in a hypothetical monocoque structural domain enclosed by the outer mold lines to determine preferred regions for primary structural members. These load paths indicate preferred regions for stress-driven members: spar webs and skin thickness buildup. Following FEM 1, Design 1 activities use the FEM 1 information to generate spar web and rib structural concepts. Structured methods for concept generation, evaluation, and selection communicate and leverage this information for effective design decisions.

Finite Element 1

The FEM 1 model is a very general shell skin with in-plane normal and shear stiffness and a core with out-of-plane normal and shear stiffness, as shown in Figure 5. Output from this model will be load path plots in the form of principal shell forces in the skins, skin thickness distribution plots, and the structural weight of the optimized skin. The analytical structural information that results from the FEM 1 model forms the basis for Level 2 concept generation.

The FEM 1 model generates optimized skin thicknesses based on strength constraints alone and provides a theoretical weight estimate. This weight estimate serves as a reference point to track the effect of each constraint set as it is added and additional model fidelity is developed, and to serve as an early predictor of true wing weight.

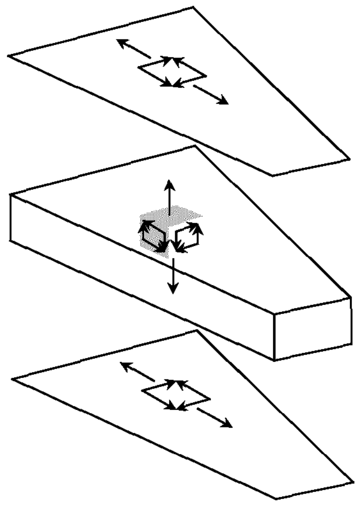

Figure 5 —Initial FEM 1 model showing upper and lower skin with in-plane normal and shear stiffness and core with out-of-plane normal and shear stiffness

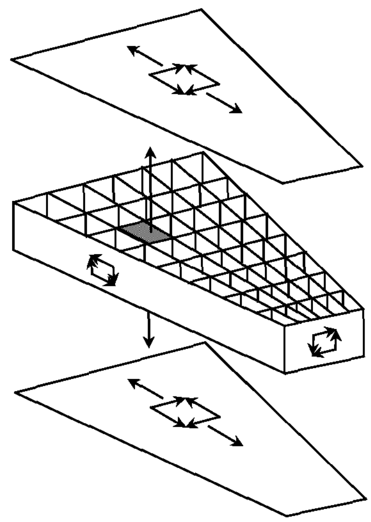

Figure 6—Final FEM 1 model showing upper and lower skin with in-plane normal and shear stiffness and lattice core with out-of-plane normal and controlled directional shear stiffness

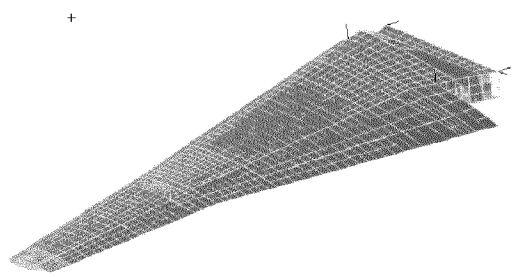

Figure 7—FEM 1 wing structural model-skin

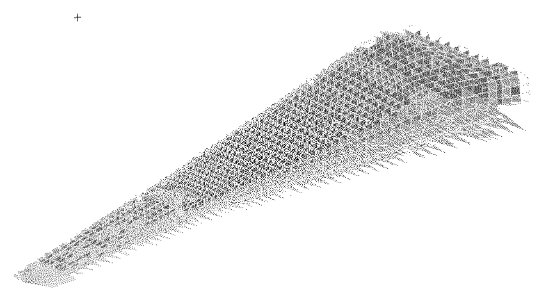

Figure 8—FEM 1 wing structural model—internal lattice structure

Structural modeling for the FEM 1 attempted to allocate bending and in-plane shear carrying capability to the wing skins and out-of-plane normal and shear carrying capability to a core filler material as shown in Figure 5. The initial FEM 1 model used shell elements for the skins and orthotropic brick elements for the core. However, in this model shear stiffness in the core changed direction with element skew and orientation.

To circumvent this problem, a modification of this FEM 1 model used a lattice of chordwise and spanwise shell elements between each brick element in the core as shown in Figure 6. These shell elements have controllable directional shear stiffness properties, while the brick elements have out-of-plane normal stiffness. Figures 7 and 8 show the wing finite element models chosen to represent the structure.

Results from the FEM 1 models indicate optimized skin weight and patterns of force flows through the structural continuum. The force flows are displayed through plots of maximum and minimum shell forces in the skins. As an example, Figure 9 shows these shell force plots for the positive dynamic gust load case applied to the FEM 1 model. Figure 10 shows the skin thickness distribution optimized over all four load cases.

The optimized skin weight for this model allows us to estimate the overall wing structural weight. Subtracting the weight of the elements representing flap and aileron sections of the wing allows estimation of structural box weight.

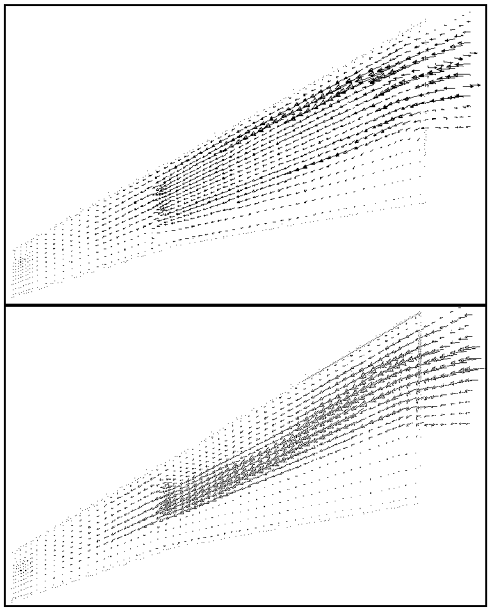

Figure 9 —Maximum/minimum principal shell forces for Critical Load Case 4, Positive Dynamic Gust at V_c-M_c Knee – upper figure—lower skin, lower figure —upper skin

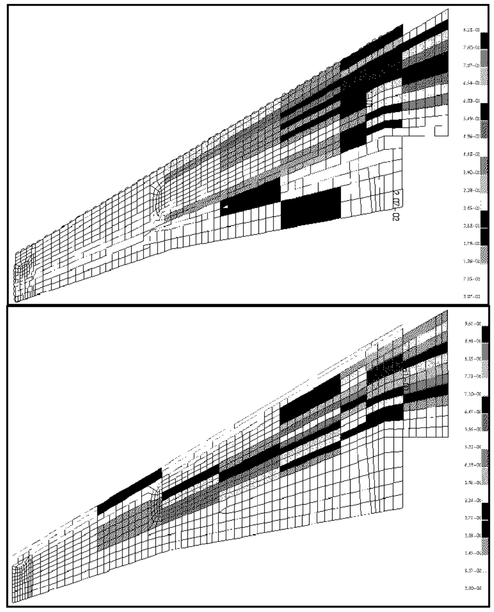

Figure 10 —Skin thicknesses optimized over all load cases. Left—Lower Skin, Right—Upper skin

The wing structural box weight was somewhat higher than expected. The primary reason for this is probably insufficient fidelity in the optimization model, causing high skin thickness over large regions because of local stress concentrations, both computational and real.

The structural information generated during FEM 1 flows into the team-based design activities of Design 1.

Design 1

Design 1 is a series of meetings that bring together the people in the organization capable of applying experience to satisfy requirements. This phase of the structural design process uses the FEM 1 results in a structured organizational process, bringing together people and technical information to evolve structural detail to the next level. Spar web concept generation takes here.

The structural designer presents to the design team the load path results of the FEM 1 model, which identify structural needs and preferences for the design based on strength. Presentation of these results graphically communicates structural needs in a format understandable by non-structural team members so they can provide critical feedback from their area of expertise. The FEM 1 model provides a scientific basis for generating structural concepts. The output of Design 1 is a manageable set of structural concepts that address spar web layout.

The Design 1 activities for the model wing structure yielded four structural concepts that were carried into Level 2. These activities included presentation of the FEM 1 models and generation of FEM 2 concepts. The structural designer presented load path results to the team in the form of principal shell force vector plots, explaining the meaning and purpose of the plots. The design team discussed spar web concept possibilities and settled on a concept pool comprised of 2, 3, 4, and 7 spar web concepts with rib design moved to the FEM 2/Design 2 phase. Design 1 meetings also established manufacturing constraints on rib design, specifying that ribs must be oriented normal to spars.

The FEM 1 models from this experiment were unable to significantly guide design activities due to at least four factors. First, the accuracy of the FEM 1 model formulation was not established, resulting in low confidence levels for the results by the structural designer and other team members. Furthermore, because the design problem was not novel (a high aspect ratio wing is a beam), the structural designer knew from experience what the force flows should be and did not gain new information from the FEM 1 model. In addition, the FEM 1 models may have been more useful had they been present to interact at an earlier stage before aerodynamic and performance design maturity when outer mold line definition could still be influenced. Finally, because there was no established relationship between the FEM 1 weight and the final wing box weight, FEM 1 model utility as feed forward devices was reduced.

Phase 2

The goal of Phase 2 activities is to integrate medium fidelity analysis and optimization results with an organizational design process to promote higher quality design decisions supported by both analysis and experience.

The purpose of the FEM 2 model is to generate useable analytical and optimization information sufficient to evaluate the spar web concepts generated during Design 1. The Design 2 activities that follow then juxtapose the structural evaluation with nonstructural evaluations (e.g., manufacturing cost estimates) to select a spar web/rib concept through structured selection methods. Additionally, Design 2 activities generate structural concepts at the next level of structural detail, stiffeners and fasteners.

Finite Element 2 (FEM 2) model

Figure 11 shows the FEM 2 finite element model for the 2-spar concept generated during Design 1. The FEM 2 finite element model adds new details to the FEM 1 model. Ideally, this would be a seamless evolutionary process with only some parts of the finite element model being replaced (in this case the shear core replaced by rib/spar web layout). The reality of current tools, however, dictated significant rework for the FEM 2 model

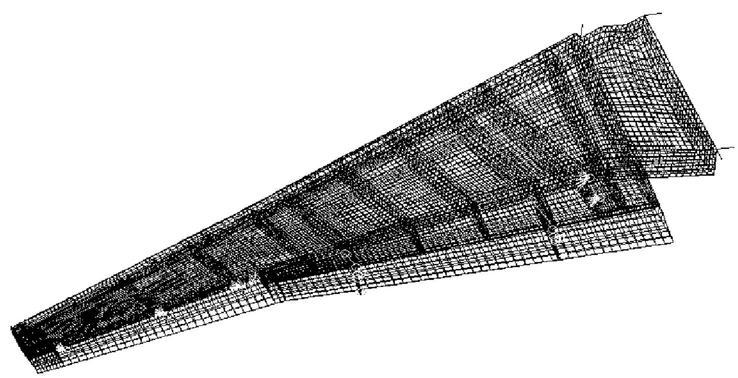

Figure 11- FEM 2 model for 2-spar concept

The FEM 2 model adds buckling, deflection, and manufacturing (minimum gage) constraints to the stress constraints considered in FEM 1. The FEM 2 model includes shell elements for skin, ribs, and spar webs and the same representative set of loads from FEM 1. To effectively design for buckling, the structural designer included circular cross-sectional area rod elements as low-fidelity stringers.

FEM 2 used NASTRAN-based optimization. In addition to skin thicknesses used by FEM 1, FEM 2 models also include spar web, rib thicknesses, and stringer cross-sectional areas as design variables. The design process experiment produced FEM 2 output for each FEM 2 concept as follows:

- A stress map for each load case
- A buckling eigenvalues and mode shape plot for the maximum bending load case
- Optimized thickness distribution for skin, spar webs, and ribs
- Optimized weight (normalized to FEM 1 weight)
- First order cost evaluation (relative ranking)

The addition of buckling constraints required high mesh density for accuracy. These finite element models included about 90,000 degrees of freedom. This caused technical difficulties because the optimization solutions with models of this size consumed large amounts of time and memory. Computer memory limitations caused significant delays and problem reformulation. These design tool limitations impacted the process and the resulting product quality.

Rib design began with the minimum number of ribs for structural connectivity for flap, aileron, systems, and landing gear. The activity then proceeded to iterate with FEM 2 model creation and solution. The structural designer placed ribs, solved the optimization model to determine buckling margin, and experientially placed or moved ribs to bring this margin to the level dictated by defined requirements.

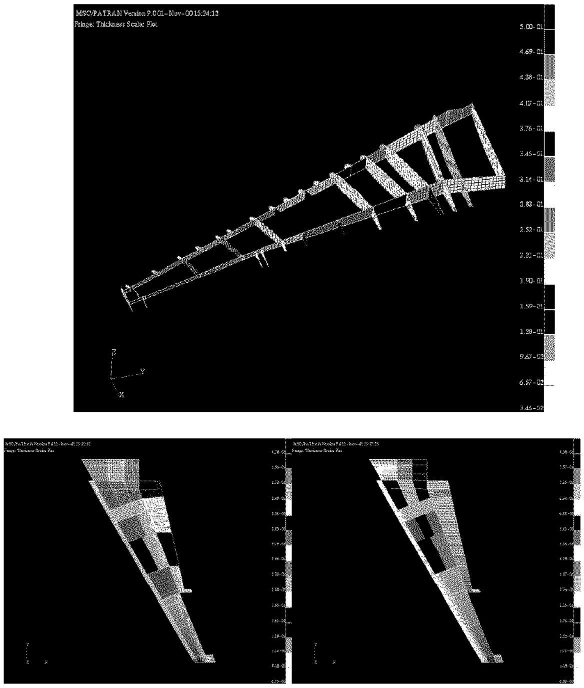

Figure 12 - FEM 2 thickness distribution results for 2 spar concept (lower skin, upper skin, rib/spar web)

Once the structural designer obtained acceptable rib layouts and buckling margins, he then optimized skin and web thicknesses using stress and buckling constraints to determine minimum weight distributions. This procedure was followed to optimize rib number and placement for each of the four concepts.

Each structural concept model contained 7 stringers, whose locations corresponded with possible spar locations. On the 7-spar model, each stringer represented a spar cap. On the 2-spar model, 2 of the stringers represented spar caps and 5 represented actual stringers.

Structural results for the FEM 2 models include stress, buckling, thickness and wing structure weight. Figure 12 shows typical optimized thickness distribution results from the FEM 2 process for the 2-spar concept.

Figure 13 shows optimized weight results for the FEM 2 models normalized to the optimized FEM 1 weight. This figure shows weight results under stress constraints alone and under stress and buckling constraints together. This plot provides a structural basis for a design decision and demonstrates the shift in structural preference depending on what constraints are considered.

The FEM 2-level structural definition enabled generation of geometric layouts to address cost, certification, accessibility, and fuel considerations (slosh, volume, and vibration). These layouts defined concepts for stiffeners, access panels, joints, fasteners, and part counts, providing information for manufacturing cost estimates. All of this information flowed into Design 2 activities to support decision-making.

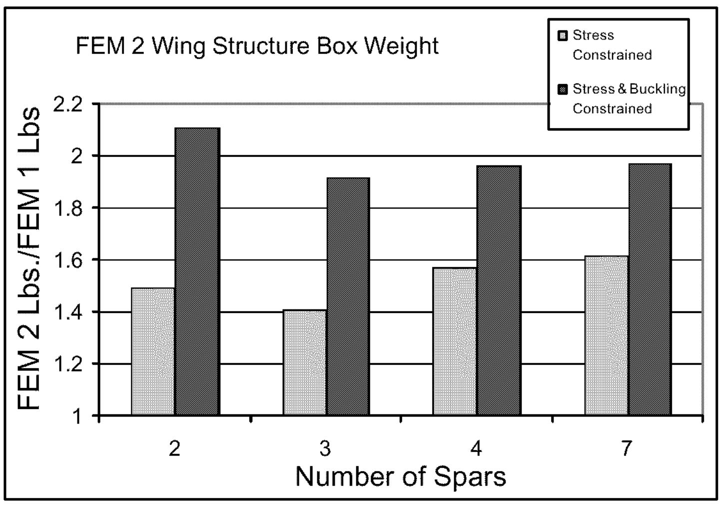

Figure 13 - Weight as a function of spar count for stress only constraint and with buckling constraint

Design 2

The FEM 2 results were presented to the full design team during the Design 2 effort; the team evaluated rib/spar web layout concepts against a manageable set of differentiating requirements, distilled from the full set of wing structural requirements. These differentiating requirements are not the typical constraints a structural designer would expect to see because all of the concepts meet key analytical constraints such as buckling, stress, and deflection.

These were built into the optimization model. Differentiating requirements are objectives such as optimized weight, estimated cost (producibility), maintainability, and other objectives that are not analytical in nature but determine the viability of each concept.

Table 1- Design 2 concept scoring matrix

	weight factor	2 Spar raw	2 Spar wtd	3 Spar raw	3 Spar wtd	4 Spar raw	4 Spar wtd	7 Spar raw	7 Spar wtd
Weight	0.30	1	0.30	4	1.20	3	0.90	3	0.90
Stiffness		1	-	2	-	3	-	4	-
Fuel Volume		4	-	3	-	2	-	1	-
Cost	0.30	2	0.60	4	1.20	3	0.90	1	0.30
Fabrication		4	-	3	-	2	-	1	-
Assembly		1	-	2	-	3	-	4	-
Accessibility	0.05	4	0.20	3	0.15	2.5	0.13	1	0.05
Inspection		4	-	4	-	2	-	1	-
Maintenance		4	-	2	-	3	-	1	-
Fuel Considerations	0.05	2	0.10	4	0.20	3	0.15	1	0.05
Certification Issues			-		-		-		-
fail safe	0.25	1	0.25	4	1.00	4	1.00	4	1.00
substantiation	0.05	4	0.20	3	0.15	2	0.10	1	0.05
Weighted Sum	1.00		1.65		3.90		3.18		2.35

Requirements reduction does not eliminate unstated requirements from consideration. Those requirements that are analytical in nature must be included in the analytical models at the appropriate level of modeling. Qualitatively evaluated requirements must likewise be evaluated at the appropriate level of modeling. The key to this process is documentation of assumptions about how each requirement will be dealt with in each modeling and design phase. The set of differentiating requirements for the model wing includes weight, cost, accessibility, fuel considerations, and certification issues.

The set of differentiating requirements goes into the concept selection matrix in Table 1 where the rows represent requirements and the columns concepts.

In the team meeting held to populate this matrix, the team scored each concept on a scale of 1 to 4, where 4 is best. These raw scores were then multiplied by weighting factors, determined by the strategic objectives for the aircraft product in the marketplace. This project team placed greatest importance on weight, cost, and certification. Each concept received a weighted sum score that represents the team's evaluation.

The results clearly show the 3-spar and 4-spar structural concepts as preferred choices. The relative difference between the 3 and 4-spar scores is insignificant compared to the scores of the 2 and 7-spar concepts. Furthermore, these choices are insensitive to adjustments to weighting factors. Even 25% changes in weighting factors yields 3 and 4-spar as clear winners. The quality of the numbers that go into the matrix is extremely important.

The Table 1 scoring matrix represents the results of extensive discussion and team learning. It brings the team to consensus and provides a more solid foundation for design decisions than mandate or vote. The numbers themselves mean very little except that they help to direct the team toward clear design decisions that balance alternatives and maintain or improve the level of team members' commitment.

FEM 2 models in the design process experiment significantly improved the quality of not only the structural weight inputs into the matrix, but also all of the other objectives. The FEM 2 models provided concrete evidence of the effects of stress, buckling, and deflection constraints on the end weight, enabling rational concept evaluation.

The other matrix inputs improved with increased structural input quality because the FEM 2 model provided the specific structural details to enable meaningful discussion and evaluation. The structural definition provided by FEM 2 models enabled preliminary design for access panels, stiffeners, and joints. This geometric configuration then allowed for evaluation of manufacturing cost, accessibility, certification, and fuel considerations (volume, slosh, and vibration).

Unlike Design 1, Design 2 took several meetings. The level of detail included in the FEM 2 models and Design 2 requirements required iteration between FEM 2 modeling and Design 2 assessment. The team refined initial FEM 2 concepts produced by the structural designer through experiential evaluation in preliminary meetings. The final FEM 2 structural models shown earlier in Figure 11 represent significant input from the design team.

Design 2/Fem 2 model and team interaction led to an evolution of detail throughout the level 2 process. Stiffener concepts emerged as part of the FEM 2 model to be carried forward into FEM 3.

The Design 2 process systematically narrowed the wing structural concept pool to the 3 and 4-spar structural concepts with buy-in from all team members. These concepts will be carried forward into FEM 3 and Design 3 for the next level of structural detail to evolve.

Phase 3

Phase 3 activities leverage the remaining design freedom to optimize and validate the final structural design against all constraints and requirements.

The purpose of the final finite element model, FEM 3, is to add structural fidelity sufficient to convey stress and optimized weight information to be able to evaluate stiffener concepts and select a full wing structural concept. The final structural design activity, Design 3, develops the structural concept with full detail.

Finite Element 3

The last stage of structural modeling, or FEM 3, addresses the final level of structural detail considered, as defined by the phase exit requirements for preliminary design. This detail includes stiffener definition and analytical cost and producibility models in addition to the FEM 1 and FEM 2 detail and constraints.

Output of the FEM 3 exercise includes analytical structural results that will then be fed into the Design 3 evaluation and selection process for the final structural concept. Objectives for FEM 3 are to generate useable information sufficient to evaluate stiffener layout concepts from Design 2 and to determine fastener requirements.

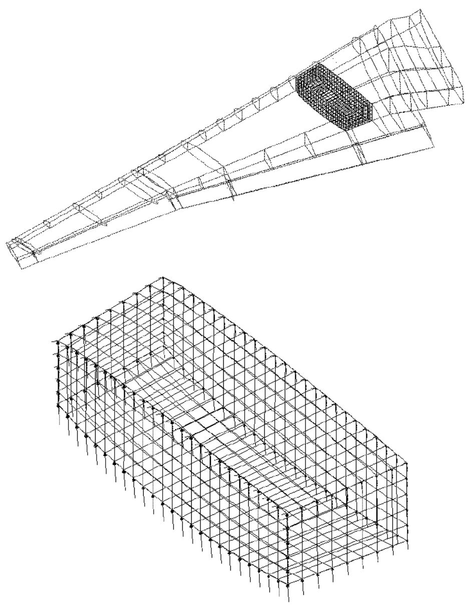

Figure 14—Example of FEM 3 model

The FEM 3 structural model, a portion of which is shown in Figure 14, consists of a master finite element model and several sub-models. The master model determines global behavior of the structure. Solution of the master model, essentially the FEM 2 solution, establishes constraints and boundary conditions for each of the sub-models. The master model contains detail similar to the FEM 2 model, including shell elements for skins, ribs and spar webs and rod elements for stiffeners.

Dividing the master model into sub-models allows for detailed design and analysis. Sub-modeling enables finer finite element meshing, improved definition of design variables, and distributed work. Boundary conditions for these models come from the master model deflection solution at the FEM 2 level. These models use NASTRAN-based optimization with constraints on stress, buckling, and deflection. Design variables for the sub-models include the number and dimensions of stringers and caps and the thicknesses of the skin, ribs, and webs. The increase in detail at this level justifies improved loads definition, incorporating design definition from previous structural design activities and perhaps expanding the load set to include additional conditions.

Design 3

The Design 3 process evaluates the structural concepts that address all of the structural and non-structural requirements. The Design 3 evaluation matrix will contain the same 5 distinguishing requirements as the Design 2 evaluation matrix. The difference between these matrices lies in the fidelity and quality of the information that goes into them and the nature of the concepts being selected. The FEM 3 models not only generate improved structural information, but also enable improved geometric definition. This improved geometric definition enables improved cost, certification, fuel, and accessibility evaluations. These evaluations must be of sufficient quality and fidelity to select and define a structural concept that meets the preliminary design phase exit requirements. Structural items for this concept include

- skin thickness distribution
- spar and rib locations
- spar cap and stiffener geometry, size and location
- fastener selection and spacing

Observations and Conclusion

This structural design process experiment provided insights into the evolutionary structural design process model and the nature of the interactions between the technical and organizational design processes. Feedback from project participants suggested the following:

- Interactions between the technical and organizational design processes exist and should be addressed through process definition and design
- An evolutionary structural design process helps to integrate design tasks
- The proposed evolutionary structural design process must adapt to organizational needs and should be refined for a specific organizational culture. The organizational processes that occur during design activities influence the design team's effectiveness in making informed design decisions that lead to a quality design.
- The design framework comprised of systematic problem definition (i.e., systems engineering requirements management and process definition) and structured solution synthesis (i.e., matrix-based scoring) improves team processes through more effective communication, problem awareness, and team member commitment. These structured design activities bring the design team to consensus, strengthening team member commitment more than decision by vote.

The evolutionary structural models reduced the technical deficiency of the structural discipline. The structural designer was an important contributor in the design process (not just an analyst) and improved his ability to communicate his needs. However, an undesirable level of technical deficiency was apparent during several attempts to assess producibility and rank concepts for cost. Producibility experts were reluctant to commit opinions until sufficient detail existed to support their opinions. This understandable reluctance reduced the effectiveness of the team.

This tendency to want to delay decisions until sufficient detail exists persisted throughout the design experiment in all disciplines. All participants wanted technical risk reduced to acceptable levels before committing their expert opinions to support design decisions. The longer the process goes without decisions, however, the more unwittingly committed the team becomes to the details being cemented into evaluation models.

The tremendous force for decision postponement must be countered by process definition that promotes decision at appropriate levels of detail and no greater. Quality designs will not result unless design freedom is exploited when it exists. To fully explore the structural design space, structural models must have complexity only as required to support informed decisions at the current level of detail. Additional detail must be withheld to prevent the process from stalling or the design from becoming committed to that detail.

The particular evolution of detail (FEM N and Design N) must be refined to meet organizational needs. When these definitions of the different finite element models and their purpose are understood, activities and decisions are traceable. There will be little need to revisit preliminary design-level activities after preliminary design review, due to requirements creep or other problems.

Acknowledgements

The authors gratefully acknowledge the superb assistance of Mr. Vladimir Sarukhanov of the Raytheon Aircraft Corporation. Vladimir's skill as a structural designer and analyst added details and definition to our study. Simply put, we could not have conducted this research without him. The authors also acknowledge the assistance of Dr. John Gallman of the Raytheon Aircraft Corporation for his support of our university research. The assistance of the design team and their openness and willingness to share their time and knowledge with us contributed to this effort immensely. Finally, we note the obvious; the personal and technical views expressed in this paper are solely our own and do not necessarily reflect those of the Raytheon Aircraft Company.

References

[1] Taylor, R.M., and Weisshaar, T.A., "Merging Computational Structural Tools into Multidisciplinary Team-Based Design," AIAA-2000-4820, *to be presented at the 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Long Beach, CA, Sept 6-8, 2000.

[2] Whitney, Daniel E., "Designing the Design Process," *Research in Engineering Design*, Vol. 2, 1990, pp. 3-13.

[3] Jackson, S., *Systems Engineering for Commercial Aircraft*, Ashgate Publishing, Brookfield, VT, 1997.

[4] Waszak, M.R., Barthelemy, J.-F., Jones, K.M., Silcox, R.J., Silva, W.A., Nowaczyk, R.H., "Modeling and Analysis of Multidiscipline Research Teams at NASA Langley Research Center: A systems Thinking Approach," *Proceedings of the 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, St. Louis, MO, Sept. 2-4, 1998.

[5] Senge, P. M., *The Fifth Discipline–The Art and Practice of the Learning Organization*, Currency Doubleday, New York, 1990.

[6] Deming, W. E., *Out of the Crisis*, MIT CAES, Cambridge, MA, 1993.

[7] Ulrich, K.T. and Eppinger, S.D., *Product Design and Development*, McGraw-Hill, New York, 2000.

[8] Eppinger, S.D., "Model-Based Approaches to Managing Concurrent Engineering," *Journal of Engineering Design*, vol. 2, 1991, pp. 283-290.

[9] Pugh, S., *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley, 1991.

[10] Dym, C.L. and Little, P., *Engineering Design: A Project Based Introduction*, John Wiley & Sons, Inc., 2000

[11] Cross, N., *Engineering Design Methods*, John Wiley & Sons, New York, 1989.

[12] Alexander, Christopher, *Notes on the Synthesis of Form*, Harvard University Press, Cambridge, 1964.

[13] Simon, Herbert A., *The Sciences of the Artificial*, MIT Press, Cambridge, 1996.

[14] Weisshaar, T. A., and Komarov, V., "Aircraft Structural Design–Improving Preliminary Design Fidelity," *Proceedings of the 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, St. Louis, MO, Sept. 2-4, 1998.